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Manickavasagam, S. and Mengüç, M.P., (1992). "The Scattering Phase Function Coefficients of Pulverized-Coal Particles in Flames", Combustion Institute, Central States Section Meeting, Columbus, OH.

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THE SCATTERING PHASE FUNCTION COEFFICIENTS OF PULVERIZED-COAL PARTICLES IN FLAMES

S. Manickavasagam and M.P. Mengüç CONF-9204103-4

Department of Mechanical Engineering, University of Kentucky,
Lexington, KY 40506

1 INTRODUCTION

The most significant mode of heat transfer in large-scale combustion systems is radiative transfer. To model such systems, radiation heat transfer should be accounted for correctly, which requires a thorough knowledge of the radiative properties of combustion products (Viskanta and Mengüç, 1987; Mengüç and Webb, 1992). It is usually difficult to calculate the properties of coal/char particles and soot agglomerates from theory, as they are non-homogeneous and irregularly shaped. Therefore, it is desirable to determine the effective radiative properties of these particles directly from experiments.

The information available for the optical and radiative properties of burning coal/char particles in the infrared region of the wavelength spectrum is scarce. Only a few studies have been published about the spectral complex index of refraction ($m_\lambda = n_\lambda - ik_\lambda$) of coal and char particles; recently, they were reviewed by Mengüç and Webb (1992). Most of the published data for the real part of the refractive index are in agreement with each other. The same cannot be said for the imaginary part; for example Brewster and Kunitomo (1984) reported k_λ values between 0.01 and 0.1, whereas most other researchers found that k_λ varies between 0.3 to 1.2 in the infrared spectrum. However, it is important to realize that the complex index of refraction data are needed to determine the required properties from the Lorenz-Mie theory, which is valid only for homogeneous spheres.

The effective absorptivity of coal particles were measured *in situ* by Grosshandler and Monteiro (1981), who observed only a slight increase in absorptivity with temperature. Solomon et al. (1986, 1987) also determined the effective absorptivity and transmissivity of pulverized-coal particles in flames in the near and the infrared spectrum. Unfortunately, these data cannot be used in detailed studies of radiative transfer.

It is more desirable to estimate the effective parameters required in the solution of the radiative transfer equation (RTE), i.e., the absorption and scattering coefficients and the scattering phase function of coal and char particles. In the present study, we determined the scattering characteristics of pulverized-coal particles heated in a premixed flame directly from experiments. The details of the theoretical models considered for data reduction were already reported in another paper (Mengüç, et al., 1991). In the following sections, first we will briefly discuss the experimental system used. After that the results will be presented and compared against those obtained from the Lorenz-Mie theory for spherical particles.

2 EXPERIMENTAL SET-UP

2.1 Burner

The burner used in this study was originally designed to generate diffusion flames. It consists of a central fuel tube surrounded by a coannular oxidizer tube, having diameters of 1 *cm* and 5 *cm*, respectively. The overall height of the burner assembly is 35 *cm*. A 8 *cm* deep layer of 4 *mm* diameter glass beads within the conical portion of the burner was used to provide stable and radially-uniform flow of the oxidizer. Coal-air mixture is fed into the central fuel tube at the bottom of the burner, which is mixed with ethylene to produce a premixed flame. The burner is mounted on a mechanism enabling vertical and horizontal translation. Fig. 1 depicts two typical flames, with and without coal particles, studied here.

2.2 Fluidized Bed for Coal Flow

A fluidized bed made of plexiglas was designed and manufactured in house. It is 44.5 *cm* high and has a diameter of 11.4 *cm*. The two ends of the bed is sealed with stop corks to prevent any leakage of coal or air carried into the burner. At the bottom end, the cork carries two tubes to supply air to fluidize coal in the bed. The smaller tube which enters the bottom of the fluidized bed ends as a helically coiled tube inside the bed and helps in circulating the air inside. The larger tube at the bottom helps in giving a forward momentum to the coal particles inside the bed. Because of the momentum gained the coal particles come out of the bed through the tube attached to the cork at the top of fluidized bed. The coal-air mixture issuing out of the bed is discharged into the center tube of the burner, where it is mixed with ethylene and is ignited at the tip of the burner. The flow rate of coal can be controlled by adjusting the flow rate of air which enters the bed. With this set up flow rates as low as 0.1 gm/min can be achieved. Since it was found that higher flow rate of coal resulted in lift-up of the flame, flow rates in present study were kept between 0.3 to 0.6 gm/min.

2.3 Optical System

In the experiments, a CO_2 laser operating at the wavelength of 10.6 μm was used. The details of the nephelometer was discussed by Mengüç et al. (1991). The light collection optics is mounted on an optical platform, which rests on a precision motorized rotary table (*Newport*, Model # 496-A). The rotary table has a bi-directional, continuous 360° rotation with speeds of upto 4°/sec, has an accuracy of 0.01° and a resolution of 0.001°. It has a 15 *cm* clear aperture at the center. The optical platform is a circular aluminum piece and has a hole at the center through which the burner assembly may be moved up or down. An optical rail is set up on the platform and an aperture of diameter 1.4 *mm* was mounted on the rail at a distance of 12 *cm* from the flame. An infrared radiation detector (*Hamamatsu*, P2613) was placed at a distance of 5.5 *cm* from the aperture to measure the scattering of the incident CO_2 laser beam by the particles. With this arrangement the solid angle subtended at the detector was in the order of 10^{-3} steradians.

The signals received by the detector were fed into an IBM PC-AT through a lock-in amplifier. Since the incident beam was modulated at a unique frequency, all extraneous signals were filtered out at the lock-in amplifier. Later, the data was transfered to a main frame computer (*IBM* 3090) for data reduction.

3 RESULTS AND DISCUSSIONS

3.1 Theoretical Results

In order to interpret the results obtained from experiments, it is useful to analyze the theoretical predictions from the Lorenz-Mie theory for spherical-shaped particles first. Such an analysis would be useful in determining the general trends in the radiative properties of particles. Also, by comparing the theoretical and experimental data, we can infer if the irregularly shaped coal particles behave similar to spherical particles.

In the experiments, two different size ranges of pulverized coal particles were used, i.e. less than 38μm and 38-53 μm. Ideally, these particles should lie in the size parameter ($x = \pi D/\lambda$) range of $x = 5.9$ and $x = 17.2$, where $\lambda = 10.6$ μm and D is the particle mean diameter. However, the electron microscope photographs revealed that there is a large number of smaller particles associated with each larger particle, indicating that fragmentation has occured during the preparation and classification of these coals. The presence of these smaller particles would change the effective scattering characteristics of the medium under consideration while performing the experiments. Therefore, it was necessary to perform the theoretical calculations using the correct size distributions.

The size distribution of pulverized-coal particles were determined from electron-microscope pictures. It was observed that the distribution was bimodal and a significant fraction (more than 95%) of particles had diameters less than 25 μm (see Fig. 2). Two different size distribution curves were fit to these data, one for the particles of diameter less than 12 μm (*regime I*) and the other for diameters greater than 12 μm (*regime II*). The distribution was expressed as a functional form given as (Viskanta and Mengüç, 1985),

$$Nf(r) = aD^{\alpha} \exp(-bD^{\gamma}) \tag{1}$$

where N is the number of particles per unit volume and a, b, α, and γ are independent parameters. To fit the size distribution the following values were used for two different regimes:

$$\textit{regime I}: \quad a = 1.15, \;\; b = 0.12, \;\; \alpha = 4, \;\; \gamma = 2 \tag{2}$$

$$\textit{regime II}: \quad a = 3.5 \times 10^{-21}, \;\; b = 0.001, \;\; \alpha = 19, \;\; \gamma = 3. \tag{3}$$

This size distribution is denoted as size A in Fig. 2. Another size distribution (size B), which was obtained by shifting the peak for *regime I* to a larger size range, was also used in the calculations to estimate the effect of the uncertainity of size distribution on the scattering coefficients. For this, the *regime I* coefficients were given as

$$a = 1.07 \times 10^{-8}, \;\; b = 0.11, \;\; \alpha = 14, \;\; \gamma = 2, \tag{4}$$

and the *regime II* coefficients were kept the same as before.

In the literature, the reported values of the real part of the refractive index of coal particles are between 1.2 and 2.0, and the imaginary part varies between 0.01 and 1.2. Preliminary calculations for spherical particles showed that the radiative properties were not strongly dependent on the real part of the refractive index. Given this, a constant value of 1.8 was employed. The imaginary part was varied between 0.001 and 2.00, and the Lorenz-Mie theory was used to determine the radiative properties of spherical particles within the diameter range of 1 to 24 μm. After that, the radiative properties of pulverized-coal clouds were calculated using the size distributions A and B.

The first three coefficients of the Legendre polynomial expansion of the scattering phase function corresponding to the size distributions A and B are plotted in Figs. 3 to 6 (theoretical results are denoted as "size A" and "size B", and they are same in all four figures). It is clear that these coefficients increase if the imaginary part is between 0.05 and 0.5, and then decrease. The effect of size distribution is minimal on the a_1 coefficient, whereas the values of the second (a_2) and the third (a_3) coefficients are higher for size distribution A, which has more smaller particles. This change can be attributed to an increase in side scattering; smaller particles scatter less in the forward direction and more in the side directions. While the first coefficient (a_1) determines the amount of forward scattering, the second and the third are also related to the amount of side scattering. Because the side scattering is increased as the size is reduced, the values of a_2 and a_3 are higher for size distribution A as compared to size distribution B.

3.2 Experimental Results

Experiments were performed using two different size range of coal particles (less than 38 μm and 38-53 μm). Measurements were taken at two different heights on the flame for the larger size range, and at three different heights for the smaller size range. The flame diameter was 22 *mm*, 23 *mm*, and 25 *mm*, at the heights of 40 *mm*, 60 *mm* and 70 *mm*, respectively, for the smaller size range, and 26 *mm* and 28 *mm* at the heights of 60 *mm* and 75 *mm*, respectively, for the larger size range. The mass flow rates of coal were between 0.1 and 0.6 *gr/min* for these experiments. The scattering readings were taken at angles between 5.5 degrees and 25.0 degrees. The scattered radiosities recorded by detectors were normalized with reflected readings.

In the experiments performed, it was not possible to detect reasonable signals beyond 25°. The theroetical results obtained from the Lorenz-Mie theory show that the scattered energy beyond 25° is small, but not negligible. In order to account for the energy scattered beyond 25°, numerical experiments were performed using the Lorenz-Mie theory. The effective phase functions were obtained for the size distributions

A and B using refractive index values of 1.8 - 0.5i and 1.8 - 0.05i. These effective phase functions were used in a forward radiation transfer algorithm to determine the exit radiosity distribution around a hypothetical flame. After that, employing only the 5° to 25° range of the radiosity distribution, the scattering phase function coefficients were determined in an inverse analysis (Mengüç et al., 1991). In subsequent runs, it was assumed that the amount of scattering after 25° was independent of scattering angle and equal to either 1/20th, 1/10th, 1/8th, or 1/6th of the value at 25°. These results showed that for both size distributions, 1/8th fraction yielded good agreement with the input data. Based on these results, the experimental data were also reduced assuming the scattering beyond 25° was uniform and equal to 1/8th of the value at 25°. While performing the numerical study more emphasis was given to arrive at the fraction which would yeld more accurate a_1 coefficient than the others. This was the criterion because of the importance of the a_1 coefficient (the asymmetry factor) in radiative heat transfer calculations.

In the inverse analysis, the single scattering albedo ω had to be guessed (Mengüç et al., 1991). It was shown before that for large spherical particles, ω weakly depends on the index of refraction and can be assumed 0.55 without introducing significant error. However, for the two size distributions used in this work, ω was more strongly dependent on the k values. From the Lorenz-Mie theory calculations, it was determined that ω=0.48 for $m = 1.8 - 0.5i$, and 0.75 for $m = 1.8 - 0.05i$. Using these two extreme values, the phase function coefficients were obtained from experimental data, following a step-function approximation (Mengüç and Subramaniam, 1990).

Figures 3 and 4 depict the scattering phase function coefficients for small range coal particles (less than 38 μm), and Figs. 5 and 6 for large range coal particles (38-53 μm). Each coefficient is represented by two parallel lines indicating their minimum and maximum values obtained from the experiments (corresponding to the different heights of coal flame). Comparison of the experimental and theoretical results show that the experimental a_1 coefficients are closer to the Lorenz-Mie theory results if the value of the em effective k lies between approximately 0.2 and 0.5. Note that these values are larger than those reported by Brewster and Kunitomo (1984) and somewhat smaller than the other reported data (Foster and Howarth, 1968).

The experimental values of the a_2 and a_3 coefficients are much higher than the values predicted by the Lorenz-Mie theory, meaning that side scattering by coal particles at $\lambda = 10.6 \mu m$ is not negligible. It is well known that irregular shaped particles scatter more in the side angles than smooth spherical particles (Wiscombe and Mugnai, 1986), indicating the irregular shape of pulverized coal particles.

The experimental results suggest that any fragmentation of coal particles affect the size distribution of particles significantly. This decrease in the mean size as well as irregularity of particles yield more side scattering than that predicted from the Lorenz-Mie theory. However, considering the fact that dominant wavelength of thermal radiation in flames is about five times smaller than that of the CO_2 laser, it is still accetable to assume coal/char particles as highly forward scattering. Then, a δ-Eddington approximation can be safely used to simplify the solution of the radiative transfer equation.

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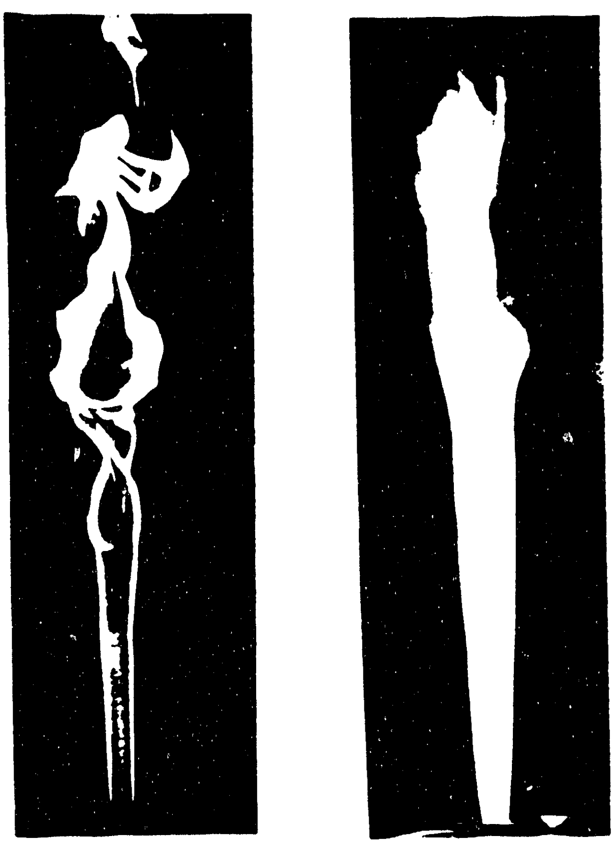

Fig.1. Flame; without and with coal part.

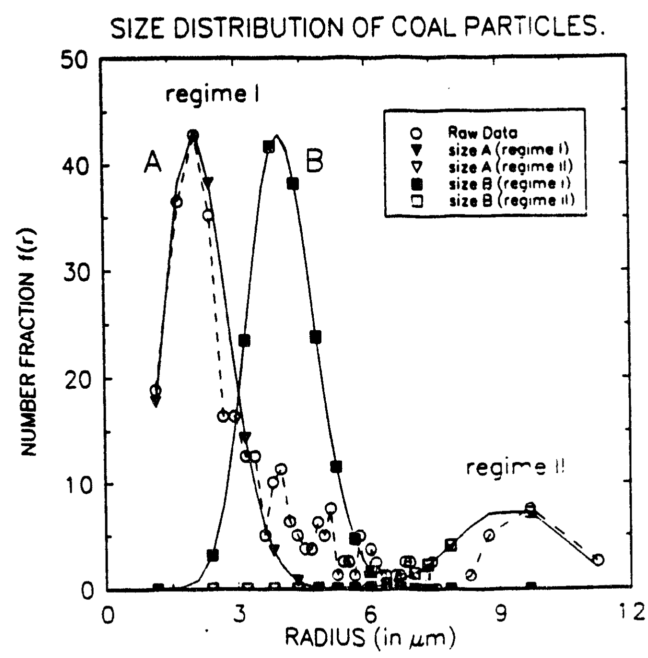

Fig.2. Experimental and theoretical coal size distributions.

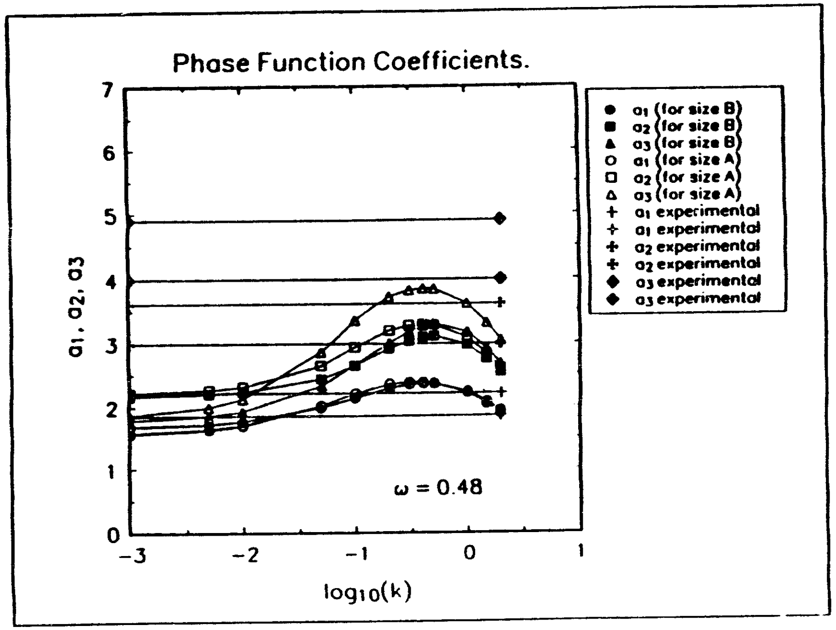

Fig. 3 Comparisons for small-size coals.

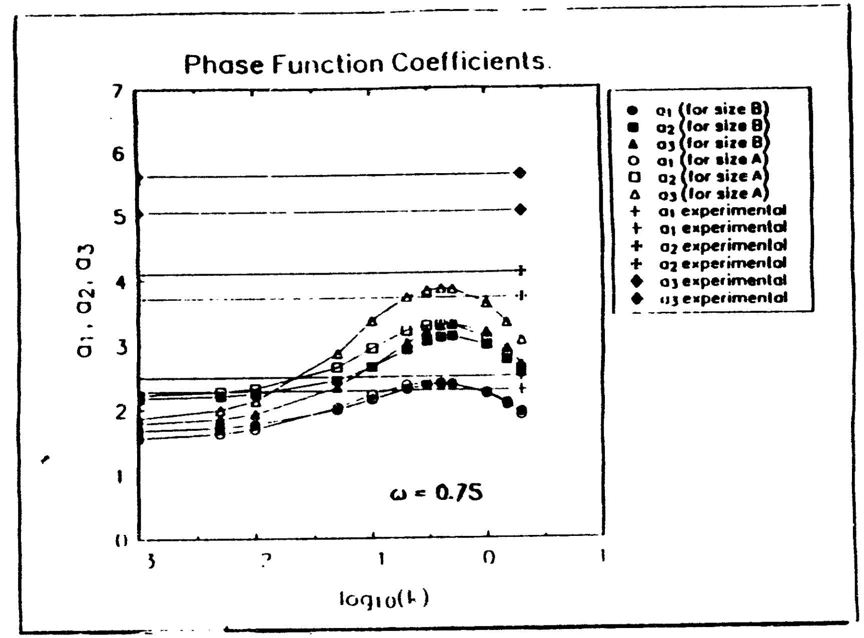

Fig. 4 Comparisons for small size coals.

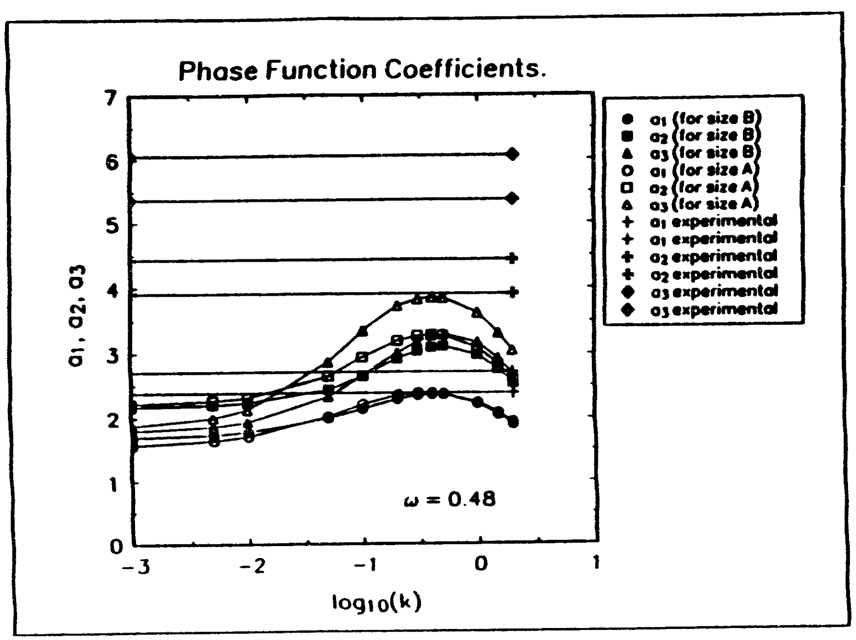

Fig. 5 Comparisons for large size coals.

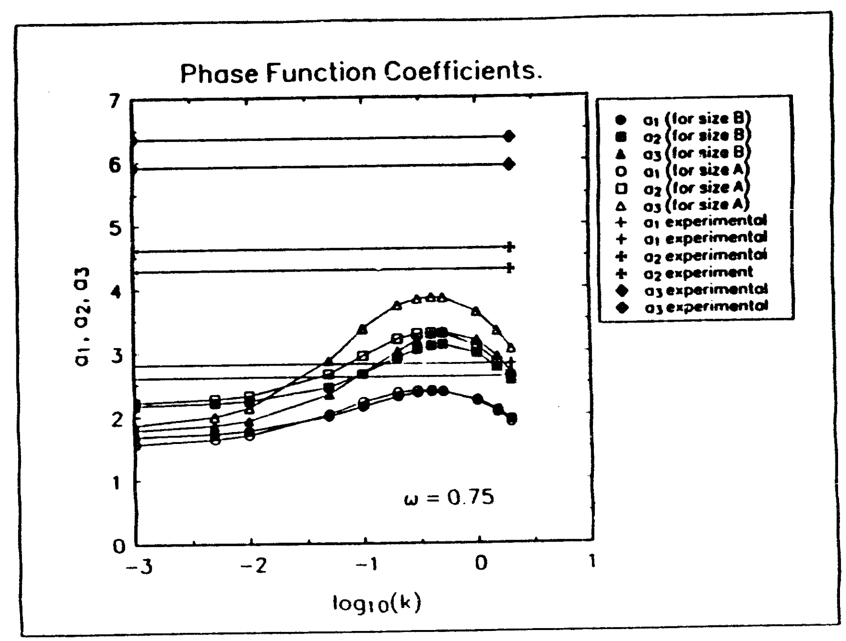

Fig. 6 Comparisons for large size coals.

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